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Monitoring and forecasting ecosystem dynamics using the Terrestrial Observation and Prediction System (TOPS)

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ABSTRACT

We present an approach for monitoring and forecasting landscape level indicators of the condition of protected area (PA) ecosystems including changes in snowcover, vegetation phenology and productivity using the Terrestrial Observation and Prediction System (TOPS). TOPS is a modeling framework that integrates operational satellite data, microclimate mapping, and ecosystem simulation models to characterize ecosystem status and trends. We have applied TOPS to investigate trends and patterns in landscape indicators using test cases at both national and park-level scales to demonstrate the potential utility of TOPS for supporting efforts by the National Park Service to develop standardized indicators for protected area monitoring. Our analysis of coarse resolution satellite-derived normalized difference vegetation index (NDVI) measurements for North America from 1982–2006 indicates that all but a few PAs are located in areas that exhibited a sustained decline in vegetation condition. We used Yosemite National Park as our park-level test case, and while no significant trends in NDVI were detected during the same period, evidence of drought-induced vegetation mortality and recovery patterns dominated the 25-year record. In our Yosemite analysis, we show that analyzing MODIS (Moderate Resolution Imaging Spectroradiometer) products (vegetation indices, absorbed radiation, land surface temperature and gross primary production) in conjunction with ground-based measurements, such as runoff, lends additional utility to satellite-based monitoring of ecosystems indicators, as together they provide a comprehensive view of ecosystem condition. Analyses of MODIS products from 2001–2006 show that year-to-year changes in the onset of spring at Yosemite were as large as 45 days, and this signal in the satellite data record is corroborated by observed changes in spring runoff patterns. Finally, we applied TOPS to assess long-term climate impacts on ecosystem condition at the scale of an individual park. When driven by projected climatic changes at Yosemite of 4–6 °C warming by 2100 with no changes in precipitation patterns, TOPS predicts significantly reduced winter snowpack and an earlier onset of the growing season, resulting in prolonged summer drought and reduced vegetation productivity.

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1. Introduction

Human transformation of the Earth has been so pervasive that only protected areas (PAs), such as national parks and reserves, retain a semblance of nature. The World Conservation Union estimates that global conservation efforts over the past three decades resulted in a phenomenal expansion of PAs, such that they now cover nearly 12.4% of Earth's land surface (Chape et al., 2003). In spite of these conservation efforts, studies have shown that the global distribution of PAs may not be optimum for conserving biodiversity (Rodrigues et al., 2004). Current conservation plans assume that the geographic distribution of species changes slowly, unless they are directly impacted by human activities. Recent studies, however, show that projected changes in climate could significantly alter such plans, requiring the establishment of new PAs or the expansion of existing PAs as the ability of current PAs to protect species diversity diminishes in the future (Hannah et al., 2007). Climate change is an important issue for many PAs in the US, particularly those in the western U.S., where significant climate impacts are already being felt (Fagre et al., 1997). Since the 1950s, remarkable changes have been reported in landscape dynamics, including shifts in the onset of spring, the timing and magnitude of surface runoff, and changes in fire regimes. Many of these recent changes are largely attributed to widespread warming

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(Hayhoe et al., 2004; Cayan et al., 2001; Dettinger et al., 2004; Westerling et al., 2006). If the current trajectory continues, climate change is likely to bring unprecedented changes to PA ecosystems and simply setting aside land may no longer be sufficient to conserve biodiversity. To assess the condition of existing protected areas we need to continuously inventory, monitor and predict both ongoing and potential changes in ecosystem conditions. Furthermore, monitoring efforts must be conducted using well documented and repeatable methods that provide consistent and comparable assessments.

Monitoring of pedological, biological, and climatological resources is expensive and time consuming, and is often difficult to accomplish within limited budgets (Herrick 2000; Palmer et al., 2002; Schreuder & Czaplewski, 1993). Fancy et al. (2009) describe a comprehensive inventory and monitoring (I&M) program for the National Park Service (NPS) that includes indicators such as changes and variability in climate, exotic plant species occurrence, vegetation cover and type, changes in snowcover, water quality and quantity, vegetation productivity and phenology. Indicators are designed to track changes in park "vital signs", which are selected by parks to "represent the overall health or condition of park resources, known or hypothesized effects of stressors, or elements that have important human values" (Fancy et al., 2009). Satellite data could be a key component of executing such a monitoring program. Remotely sensed data, desired in PA assessment because of the low data collection footprint, have been used to map features such as burned areas, burn severity, land cover type, and invasive species extent (Gross et al., 2006; Cohen & Goward 2004). One benefit of remote sensing for PA monitoring is that it provides complete spatial coverage, versus point or plot samples from which it may be difficult to provide an overall assessment for the entire PA. Historically, however, remote sensing studies over PAs have been largely limited to the use of very high spatial resolution (but low temporal resolution) satellite or airborne data. These studies, though providing the best inventory of PA resources, tend to be expensive, complex, and difficult to repeat.

Recent advances in moderate resolution remote sensing data offer a strategic complement to high spatial resolution inventories. Satellite-based data from sensors such as the Moderate Resolution Imaging Spectroradiometer (MODIS) offer daily/weekly data at a resolution of 250–1000 m (Justice et al., 1998). Data from MODIS provide a capability for regular ecosystem monitoring for PA vital sign indicators such as phenology, snow cover, surface temperature, and vegetation productivity. State-of-the art processing algorithms facilitate accurate geometric, radiometric and atmospheric corrections leading to robust estimates of land surface properties that can be directly used in monitoring systems. These newly available operational products, when integrated into the I&M program or other PA monitoring systems, have immense and yet to be realized potential for PA management. Lack of remote sensing expertise and the need for large computational resources, beyond the scope of many PA stewardship organizations, are often cited as key issues for their limited use to date.

While satellite or ground-based data can provide information about trends and variability in key ecosystem properties, understanding the mechanisms behind them involves careful analysis of additional data, such as climate records and estimates from simulation models. Models are particularly important for predicting the future states of ecosystems that may result from various forcings, such as climate change and land use changes, as analysis of these forcings requires the use of simulation models (Running et al., 1989; Nemani et al., 2003a). Such models, when properly calibrated and tested, are valuable tools for asking "what if" questions that allow PA managers to assess the impacts of external forcings and various management options. For example, models such as the Regional Hydro-Ecological Simulation System (RHESSys) have been used to predict changes in ecosystem properties in response to climate change over national parks (Baron et al., 2000). While valuable, the scientists conducting these modeling analyses rarely have sufficient resources to adapt the models for use in an operational setting.

All the key components of a system that could accomplish monitoring, modeling, and forecasting of PA ecosystems exist at various levels of sophistication. What is needed is to integrate these components into a robust system that PA personnel, who often lack the experience in various components, can use operationally. Here we describe our efforts at building such an integrated system. Funded by the National Aeronautics and Space Administration (NASA), the Terrestrial Observation and Prediction System (TOPS) is a data and modeling software system designed to seamlessly integrate data from satellite, aircraft, and ground sensors with weather, climate, and application models to expeditiously produce operational nowcasts and forecasts of ecological conditions (Fig. 1, Nemani et al., 2003a, 2007; White & Nemani 2004; Ichii et al., 2008). TOPS provides reliable data on current and forecasted ecosystem conditions through automation of the data retrieval, preprocessing, integration, and modeling steps, allowing TOPS data products to be used in an operational setting for a range of applications. TOPS is designed and implemented following the principles laid out in the Global Earth Observing System of Systems implementation plan (GEOSS, 2005).

Though TOPS has already been used in the development of a variety of applications, from simulating irrigation requirements of vineyards to monitoring global net primary production (Nemani et al., 2003b; Nemani et al., 2007), its application for PA management leverages all of its key components: monitoring, modeling and forecasting, as well as a sophisticated data gateway that will allow access to organized and highly customized information.

This paper is organized as follows: first, we describe TOPS and its components; second, we provide a continental analysis of PA ecosystems over the past 25 years (1982–2006) using coarse resolution satellite data; third, using Yosemite National Park (hereafter referred to as Yosemite) as a demonstration of TOPS regional analysis capabilities, we evaluate the application of moderate resolution satellite data for monitoring park vital signs, understanding ecosystem controls of interannual variability using simulation models, and forecasting the impact of potential climatic changes on Yosemite ecosystems; and fourth, we describe a data gateway for accessing TOPS data and information.

2. Terrestrial Observation and Prediction System

2.1. TOPS overview

The concept behind TOPS originated with earlier work on the integration of satellite data with ecosystem models (Running et al., 1989; Nemani et al., 1993). This effort required careful adaptation of one-dimensional simulation models to a two-dimensional land surface, which required spatially continuous, gridded data on soils, vegetation and climate (Running et al., 1989). Satellite data provided the necessary data inputs for much of the required information on land use/land cover, and for estimates of biophysical properties such as vegetation leaf area index (LAI) (Nemani et al., 1993). Spatial aggregation of landscapes into functionally similar units and routing of water between and among these units for simulating streamflows came next (Band et al., 1993; Tague & Band, 2004). Sophisticated gridding routines helped in the creation of spatially continuous climate fields using a limited number of climate observations (Thornton et al., 1997; Jolly et al., 2005). TOPS leverages this historical work, focused primarily on retrospective analysis of ecosystems, and includes additional functionality that enables simulation models to be run in near real-time, which provides a new capability for operational nowcasts and forecasts. During the past two decades, advances in information technology including the rapid expansion of the world wide web, exponential increases computing power and storage, and

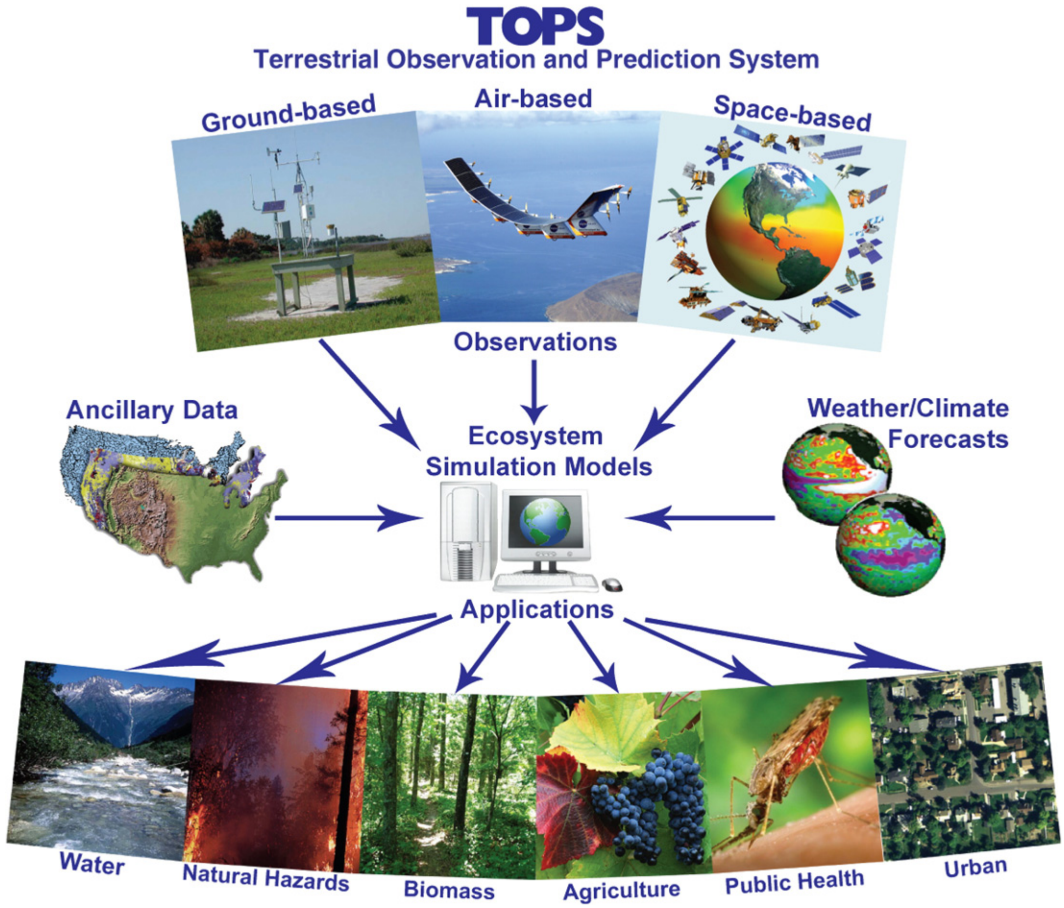

Fig. 1. A schematic representation of data-model integration enabled by TOPS for serving a variety of applications. TOPS is designed and implemented following the principles laid out in the GEOSS (Global Earth Observing System of Systems) implementation plan.

the proliferation of publicly available satellite and climate data, have all contributed to the creation of TOPS in its present form.

Given the diversity of data sources, formats, and spatio-temporal resolutions, system automation is critical for the reliable delivery of data products for use in operational decision making (Fig. 2). Ingested data go through a number of preprocessing filters in which each parameter is mapped to a list of attributes (e.g., source, resolution, and quality). Upon completion of the pre-processing steps, each data field is self-describing to the TOPS component models such that any number of land surface models can be run without extensive manual interfacing. Similarly, the model outputs also pass through a specification interface, facilitating post-processing so that model outputs can be presented in a format that is designed for use in reporting and decision-making, as opposed to just another stream of data (see Nemani et al., 2007 for further details).

Much of the flexibility in TOPS comes from the design of the key software components and their interactions. The core of TOPS modeling system is the Java Distributed Application Framework (JDAF, Votava et al., 2002), which provides a unified interface to a large set of data processing and image analysis algorithms that are deployed to pre-process and post-process inputs and outputs of the TOPS ecosystem models, as well as to manage execution of the models. Additionally, JDAF provides interfaces to the database system and to TOPS' web services capabilities, providing seamless access to both data and services provided by TOPS. In order to further improve automation of the data processing and model execution, we have developed an experimental planner-based agent (IMAGEbot) (Golden et al., 2003), which automatically generates the sequence of processing steps needed to perform the appropriate operations required in response to user-defined goals. JDAF provides of all of the processing components of the system and IMAGEbot determines which of the components should be used and the appropriate processing steps to achieve a user-specified goal. IMAGEbot then creates a processing plan and executes it. This adds flexibility to the TOPS system and accelerates the integration of both new datasets and models for use in the development of new applications.

2.2. Components of TOPS

2.2.1. Climate gridding

Gridded climate surfaces are a key input to many component models within TOPS, and TOPS includes functionality for deriving gridded climate surfaces from networks of meteorological stations. To create a gridded climate surface, JDAF first fetches the necessary weather data from station locations in the region of interest from predefined sources, checks for consistency against historical averages, fills missing values from additional sources, flags missing values, and finally converts these observation records to data structures and passes them to the Surface Observation and Gridding System (SOGS, Jolly et al., 2005), a component model within TOPS. SOGS is an operational climate-gridding system, and a simpler version of DAYMET (Thornton et al., 1997), that uses maximum, minimum, and dewpoint temperatures, in addition to rainfall, to create spatially continuous surfaces for air temperatures, vapor pressure deficits, and incident radiation. The cross-validation statistics returned from SOGS allow the system to decide if the user-specified requirements for accuracy have been achieved, or if alternative gridding methods need to be found.

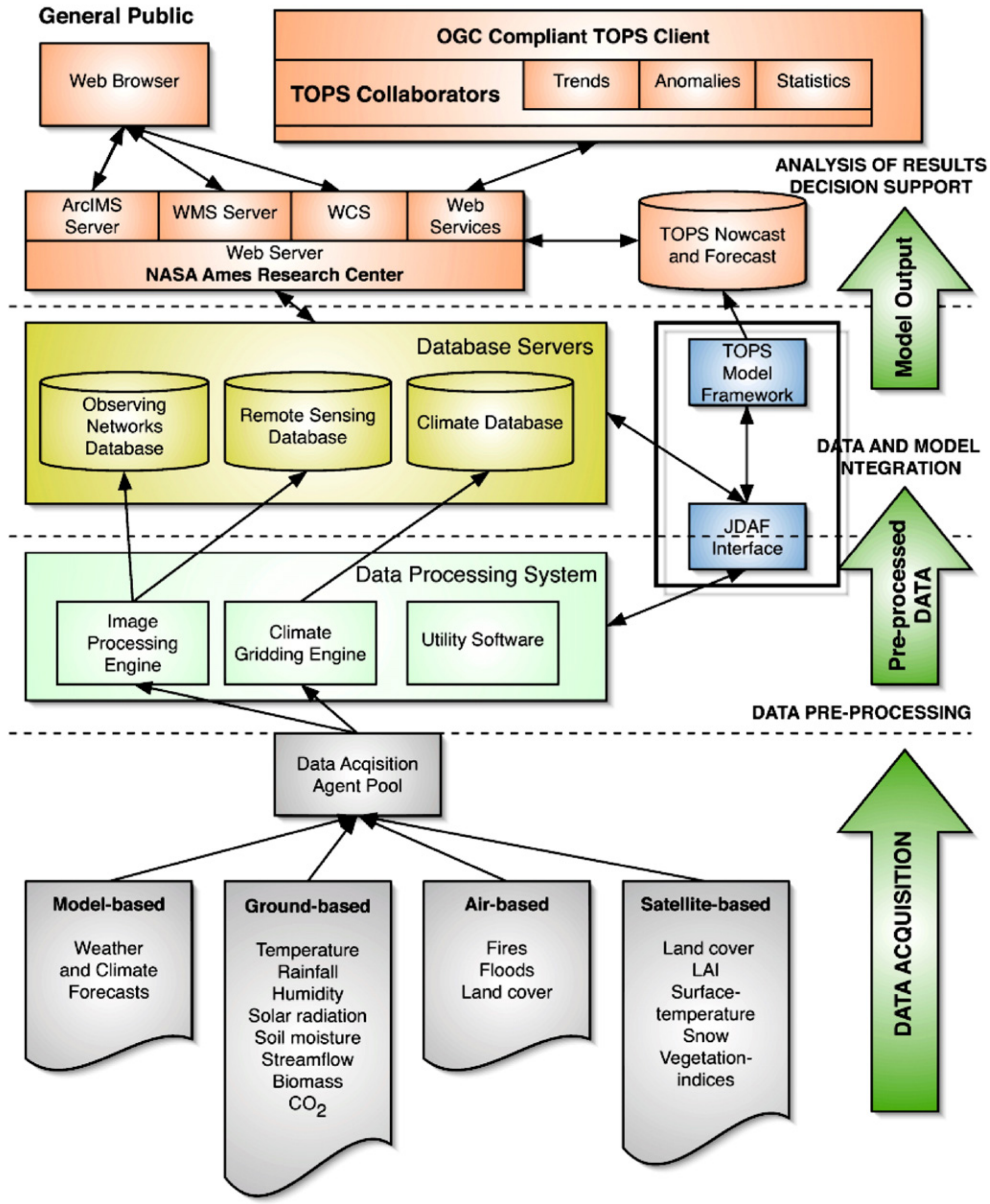

Fig. 2. TOPS architecture highlighting the data-model integration aspects of the system. Heterogeneous data are acquired from a number of different sources and subsequently pre-processed and screened for quality and integrated into the internal database system. JDAF then coordinates the data-model interactions and execution of the models. Following the execution, the new data products are distributed using a number of different interfaces including the TOPS Data Gateway (https://ecocast.arc.nasa.gov).

2.2.2. Satellite data

TOPS has access to a number of satellite data sets produced and processed by either NASA, the U.S. Geological Survey or the National Oceanic and Atmospheric Administration (NOAA). This access involves machine-to-machine, web-based ordering, and FTP pushes for routine data sets such as those from the NOAA Geostationary Operational Environmental Satellites (GOES). The data acquisition and processing steps are determined by user requirements, which may include, for example, obtaining LAI and snowcover data with the following constraints: a minimum resolution of 1 km, a weekly time interval, and a specification to obtain the highest possible quality data available. JDAF fetches all of the metadata files relating to the LAI product to be evaluated and screened for quality and prepares a list of 'tiles' (the 1200 × 1200 km area used in MODIS processing) covering the geographic area of interest and meeting the quality criteria. A request is sent to the archival site (for example, the USGS EROS Data Center). When the order is ready for download, JDAF collects the order and updates the internal database. Once the data are stored locally, JDAF initiates a series of actions, including the creation of mosaics, interpolation of missing values, regridding, and reprojection.

In many cases, data available from the Distributed Active Archive Centers (DAACs) may be 2–8 days old. While this may not pose a significant problem for geophysical fields such as LAI that vary slowly, snow cover can change dramatically in a week. To deal with these situations, TOPS also has the ability to ingest and use MODIS data from Direct Broadcast readouts available throughout the United States.

2.2.3. Modeling

A number of component models have been incorporated into TOPS, including publicly available versions of CASA (Potter et al., 1993), LPJ (Sitch et al., 2003), VSIM, (Pierce et al., 2006), SWAT (Gassman et al., 2007), and WRF (Shamarock et al., 2005). Each of the models has different strengths and is suited to different applications. The primary ecosystem modeling component of TOPS used for the PA monitoring applications described here is derived from the Biome BGC model (Thornton et al., 2002; White et al., 2000; White & Nemani 2004), which in turn is based on the Forest BGC model (Running & Coughlan, 1988). TOPS uses BGC in both diagnostic and prognostic modes. The prognostic Biome BGC model simulates states and fluxes of ecosystem carbon, nitrogen, and water with prognostic phenology (White et al., 1997), mass and energy balance, and considers atmospheric and structural disturbances. The diagnostic version of the Biome-BGC water flux model is based on a Penman–Monteith approach relying on satellite-derived LAI and surface meteorology. Daily water fluxes calculated include evapotranspiration (ET), runoff, and soil water content. ET is calculated as the sum of transpiration, soil evaporation, canopy evaporation, and sublimation. Runoff is calculated as soil water in excess of soil water holding capacity. Soil water content, which in turn affects leaf water potential and stomatal conductance, is the balance between inputs (snowmelt and precipitation) and outputs (ET and runoff, calculated using a bucket model with a simple routing scheme). In the diagnostic mode TOPS carbon fluxes are calculated based on a light-use efficiency model: productivity $=\varepsilon\times \mathrm{APAR}\times f$ (environment) where ε is the dry matter conversion efficiency, a biome-dependent variable derived from Yang et al., 2007; f(environment) is a multiplier set as the minimum of limitations from leaf water potential, night minimum temperatures, and vapor pressure deficit (each is a zero to one scalar, also used for water fluxes); and APAR is absorbed photosynthetically active radiation (MJ m^{-2}), calculated as photosynthetically active radiation (PAR) multiplied by the fraction of photosynthetically active radiation (FPAR) absorbed by plant canopies (Myneni et al., 2002).

TOPS outputs are routinely compared against observed data to assess spatio-temporal biases and general model performance. In the case of snow pack dynamics, for example, we performed a three-way comparison among model-, observation-, and satellite-derived fields of snow cover expansion and contraction over the Columbia River Basin (Ichii et al., 2008). Variables related to water and carbon fluxes, such as evapotranspiration, gross primary production (GPP), and net primary production (NPP) (Yang et al., 2007), are tested against FLUXNET-derived data at select locations representing a variety of land cover/climate combinations. Similarly, the Soil Climate Analysis Network (SCAN) of soil moisture measurements, USGS National Streamflow Information Program (NSIP) streamflow measurements, and the United States Department of Agriculture SNOw TELemetry snow data provide valuable data for verifying the hydrology predictions from TOPS.

2.2.4. TOPS data gateway

The volume of data available from Earth observing satellites, in combination with issues associated with data access and processing, have historically been significant barriers to more widespread use of satellite data by PA managers. Previous efforts to apply satellite observations for PA management have been limited to short-term studies in a single park or region, largely due to the lack of a system capable of automating the analysis and delivering the results of the analysis to PA managers. The NASA Earth Observing System data gateway, the standardized atmospheric correction and orthorectification routines included in the standard MODIS processing, and the supplemental data processing capabilities provided by TOPS have done much to address these barriers. However, operational use of satellite-derived indicators of ecosystem conditions for PA management (in addition to many other applications) requires not only that the data ingestion and processing be automated, but also that an interface exists through which PA managers can easily browse and composite data, query features of interest, examine time series, and retrieve the relevant datasets for patterns or events of particular interest. In addition, the interface must provide access to both standardized summaries of the time series of satellite observations (e.g., graphs of park-wide averages and trends at significant locations, and maps of sustained trends or persistent anomalies) as well as the supporting data on which these summaries are based.

To address this need, we have implemented a browser-based data gateway for TOPS for use by PA managers and personnel (Fig. 3). This gateway is implemented with open source software applications and adheres to the Open Geospatial Consortium's web service protocols (e.g., Web Map Service, Web Coverage Service, http://www.opengeospatial.org/standards) to maximize data interoperability. The current software is based on GeoServer, the PostGrid raster indexation engine, and a WMS/WCS server. The TOPS data gateway allows PA managers to use a web browser to access dynamic maps of significant trends and anomalies in key indicators of ecosystem conditions, view and query time-series of data from satellites and ecosystem models, composite layers to examine features of interest, and retrieve data in multiple formats for further analysis. The development of this end-to- end, satellite-to-desktop automated processing and delivery capability is designed to overcome the primary obstacles to routine use of satellite-derived indicators of ecosystem condition by PA managers.

3. TOPS applications

To address the focus of this special issue i.e. remote sensing of PAs of North America and to showcase many of the capabilities of TOPS for understanding the past, monitoring the present and preparing for the future, we describe both a continental and a local application of TOPS for PA monitoring. The continental application provides a preliminary analysis of trends in PAs of North America over the past 25 years (1982– 2006) using coarse resolution satellite data. The local application focuses on Yosemite in the Sierra Nevada Mountains of California using TOPS capabilities for monitoring, modeling, and forecasting.

3.1. Satellite monitoring of PAs in North America

There are over 650 PAs in North America covering the entire range of climatic conditions from tropical to the arctic (Chape et al., 2003). Their size varies from a few acres to millions of acres. A variety of environmental pressures ranging from urbanization, pollution and climatic changes are known to impair ecosystem function within these PAs. Photosynthetic capacity of an ecosystem provides an integrated measure of ecosystem condition that can be detected by satellites. Satellite-derived indices such as the normalized difference vegetation index (NDVI) capture differences in reflectance between red and near infrared wavelengths and have been found to be strong indicators of photosynthetic capacity (Goetz et al., 2006; Running & Nemani 1988). Throughout the rest of this paper, we use NDVI as a generalized indicator of photosynthetic capacity.

To detect long-term trends in NDVI over North American PAs we used the NDVI data derived from the Global Inventory Modeling and Mapping Studies (GIMMS) dataset version G (Tucker et al., 2005), spanning from January 1982 to December 2006. The GIMMS-G data set is derived from the NOAA Advanced Very High Resolution Radiometer (AVHRR) satellite data as a 15-day composite of maximum NDVI composite at a spatial resolution of 8×8 km^2. Vegetation growing season onset, as well as length, varies from year to year, but growing season peaks in NDVI tend to be quite conservative. Therefore, changes in peak NDVI reflect systemic changes in ecosystem condition. While earlier studies focused on growing season dynamics, here we concentrated our efforts on analyzing trends in peak NDVI (Goetz et al., 2005). We selected the highest NDVI value for each pixel in each year of the 25-year record for further trend analysis.

3.2. Monitoring of Yosemite National Park using TOPS

Yosemite National Park is one of the most popular national parks in the country, and occupies nearly 3000 km^2 of PA, with elevations

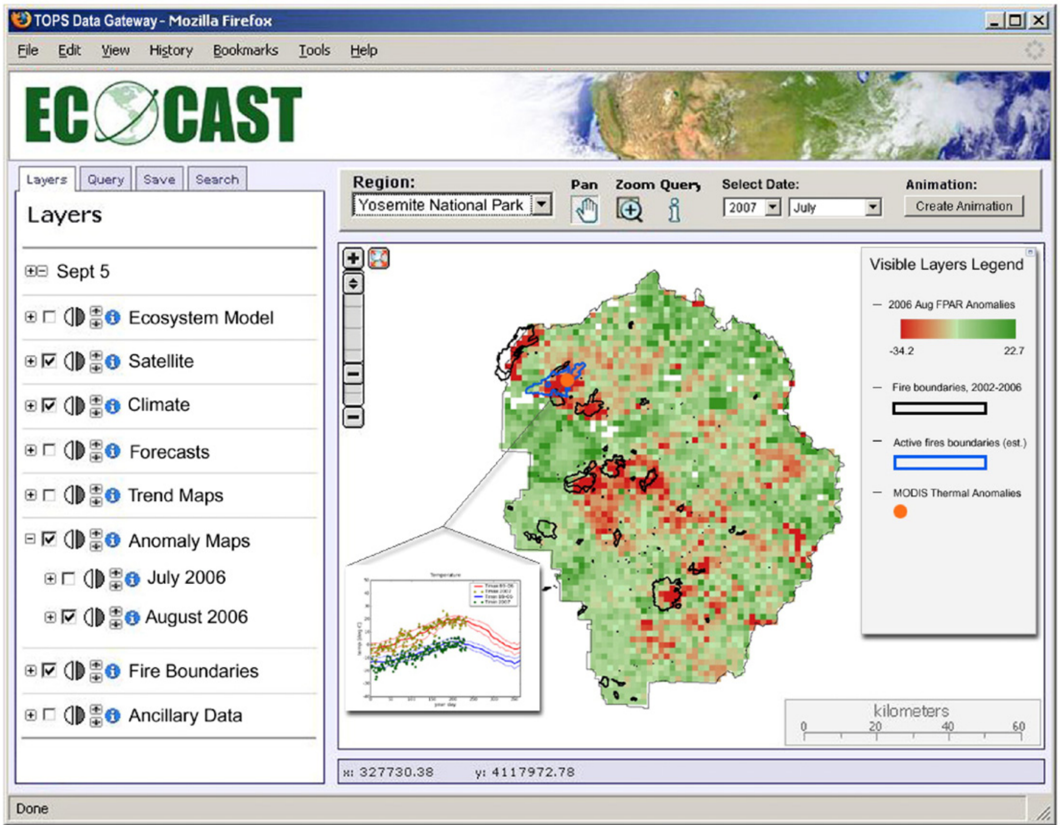

Fig. 3. An interactive data gateway to TOPS data. Users have access to both supporting raster raw data as well as data summaries such as trend and anomaly maps, animations of data time series, and queries of historical and forecast conditions.

ranging from 600 to 4000 m, in the central Sierra Nevada Mountains, in northern California, USA (latitude 37.6 N, longitude 119.7 W). The climate is characterized by warm, dry summers and cold, wet winters. Average annual precipitation in Yosemite Valley (1220 m) is 945 mm (1960–1990), 85% of which falls between November and March as snow. Soils in Yosemite are derived mainly from Mesozoic-aged granitic bedrock, and soil depth is highly variable depending on local site conditions (Van Wagtendonk & Root, 2003).

Because providing consistent long-term monitoring and forecasting of PA ecosystems is our primary goal, TOPS capabilities for nowcast monitoring or seasonal forecasting are not emphasized in this paper. Instead, we focused on using the best quality data available as quickly as possible to assess park ecosystem conditions. Surface weather observations from NOAA and satellite data from NASA provide two reliable sources of information for vital signs monitoring.

3.2.1. Satellite

MODIS is a key instrument onboard the TERRA and AQUA platforms of NASA's Earth Observing System, collecting data globally twice per day in 36 wavelength bands from visible to far infrared at spatial resolutions of 250–1000 m. The daily data are processed with community-accepted algorithms to produce standard global products from surface reflectances to higher level biophysical products such as FPAR, LAI, GPP, and NPP (Justice et al., 1998). For the first time in satellite remote sensing history, operational products are being produced every 8 days that are specifically designed to encourage the development of applications such as the present study.

We used the following five collection 4 MODIS products from 2000–2006 in this study: snow cover, land surface temperature (LST), NDVI, LAI/FPAR, and GPP. Snow cover was calculated from the 500 m 8-day MODIS snow cover product (MOD10A2, Hall et al., 2002). In this product, snow is detected using a Normalized Difference Snow Index that is estimated using daily data from red, near infrared and shortwave infrared wavelengths. In the MOD10A2 8-day composite snow cover product, a pixel is identified as snow if snow is present on any of the eight days. LST was calculated from the 1 km 8-day product (MOD11A2, Wan et al., 2004) in which LST is estimated using the split-window technique and found to be accurate to within 1 degree K (Wan et al., 2004). The 8-day LST product represents an average LST value for all clear days over the 8-day period. NDVI was calculated from the 500 m 16-day MODIS VI product (MOD13A2) (Huete et al., 2002) to evaluate interannual changes in peak NDVI. Unlike other products, NDVI products are provided for 16-day compositing periods using MODIS surface reflectance products (MOD09), which are atmospherically corrected for molecular scattering, ozone absorption, and aerosols (Vermote et al., 2002). For more frequent updates of VIs, which can be necessary for monitoring vegetation phenology, we used the 8-day MOD09 red and near infrared reflectances to compute NDVI. Fourth, we used LAI and FPAR data from the 1 km 8-day LAI/FPAR product (MOD15A2) derived using MOD09 data and a land cover dependent Look-Up-Table for translating reflectances to LAI and FPAR (Myneni et al., 2002). GPP was calculated from the 1 km 8-day product (MOD17A2), which is based on a light use efficiency model that incorporates MODIS LAI/FPAR data, meteorological data from a General Circulation Model (Running et al., 2004).

Park-wide averages for each of the 8-day periods in a year were computed by averaging all pixels in the park for snow cover and over vegetated pixels for LST, FPAR and GPP. To assess changes in peak NDVI, annual peak NDVI for each 500 m pixel was subtracted from the climatological peak NDVI computed for years 2001–2006. We used the PAT (Percent Above Threshold) approach outlined in White and Nemani (2006) to characterize the phenological cycle at Yosemite. We considered Yosemite to be a single phenoregion for this analysis (White et al., 2005). Consequently, a single park-wide threshold, half the annual climatological amplitude, was computed. For each 8-day period for all six years, the percent of pixels within the park exceeding the threshold was computed. The progression of PAT is considered to be a landscape-level phenological metric for a given phenoregion. While a given value of PAT is not necessarily associated with a particular phenological event, it provides a standard measure that can be calibrated against observed events. Similarly, the methodology allows disaggregation of Yosemite into homogenous units based on topography, vegetation type, soils, etc. for each of which a PAT can be computed.

3.2.2. Climate

Weather data (maximum and minimum temperatures and rainfall) from 8 stations located within the park and over 10 stations in close proximity were obtained from the NOAA Cooperative Observer Network for all available years (1901–2003). None of the stations in and around the park are part of NOAA's primary weather network. Consequently, data from these stations are only available with delays of several months. Since these data go through extensive quality control, they represent the best available information on climate variability for the park. The daily station data were gridded using SOGS to produce spatially continuous meteorological fields for 1982 to present, overlapping the satellite record. These grids were used for further analysis of trends and variability, and as inputs to ecosystem modeling.

3.3. Forecasting impacts of climatic changes on Yosemite ecosystems

Prior to addressing climate change impacts on ecosystems at Yosemite, we tested the ability of TOPS to simulate interannual variability in ecosystem dynamics particularly snow cover, runoff and photosynthesis. TOPS was used in prognostic mode, following a spin-up run, to simulate water, carbon and nutrient fluxes over Yosemite from 1982–2003. Soil and vegetation data used were the same as those used in standard diagnostic runs. Monthly anomalies of modeled GPP were compared against NDVI anomalies from GIMMS from 1982–2003. Modeled snow cover (averaged to 8-day periods) was compared to MODIS snow cover from 2001–2003. Ground-based data records and observations in Yosemite available for verifying MODIS or model-based estimates of park-wide conditions are limited. Only monthly snow data at two locations (Yosemite Headquarters and Tenaya Lake) and daily runoff measurements for the Merced and Toulumne Rivers are available. Annual data on burned area boundaries within Yosemite as well as insect damage surveyed by the United States Forest Service proved important for interpreting satellite-based vegetation anomaly estimates. To evaluate model and MODIS-derived GPP we used GPP data collected at the nearest Fluxnet site with comparable vegetation patterns, located at the Blodgett Forest Research Station, approximately 100 km northwest of Yosemite with comparable vegetation patterns (Yang et al., 2007).

To demonstrate TOPS capabilities for addressing climate change impacts on PA ecosystems, we used a prognostic version of TOPS to simulate changes in snow dynamics, and seasonal and annual GPP, which are key components of ecosystem integrity and condition. We used downscaled climate projections from the California Climate Change Center, which used a varied set of climate models and emission scenarios from the Intergovernmental Panel on Climate Change Fourth Assessment Report (AR4) to estimate possible future climatic changes over California (Hayhoe et al., 2004). As part of the scenarios assessment, a statistical technique using properties of historical weather data was employed to correct model biases and "downscale" the global model simulation of future climates to a finer level of detail, i.e., onto a grid of approximately 12 km (Maurer et al., 2007). Our own analysis of AR4 models over California suggested that only the Geophysical Fluid Dynamics Laboratory model under the medium-high emissions scenario was able to capture the historical climate variations over Yosemite. As such, in our analysis we used only these climate model simulations. It is important to note that large variations exist among the climate models, giving rise to large uncertainties in projected climate. These analyses are meant only to provide an assessment of *possible* future conditions at Yosemite.

We realize that uncertainties associated with downscaling, particularly with reference to lapse rates in mountainous terrain, are currently large for ecosystem impact assessments (Lundquist & Cayan, 2006). More work is needed on techniques for downscaling general circulation model simulations of future climates that incorporate the dynamic associations between local lapse rates and large-scale upper atmosphere dynamics. Consequently, we limit our interpretation of ecosystem responses to climate change as a park-wide composite signal rather than distributed responses. Daily outputs from 1950–2000 and 2050–2100, representing the past and future conditions, are converted and presented as monthly means for snow water and GPP, as well as annual trends in GPP.

4. Results and discussion

4.1. Satellite monitoring of PAs in North America

Widespread declines in peak NDVI occurred over many PAs of North America from 1982–2006 (Fig. 4). Of the 600 PAs in North America, 179 are located in areas that had a statistically significant decline in peak NDVI ($P<0.05$) with only 8 PAs located in areas showing an increase. Only tundra ecosystems of the far North exhibited significant greening. The declining trends in peak NDVI appear to be stronger and cover a larger area relative to those reported by Goetz et al. (2005) from 1982–2003. It is important to note that the coarse resolution nature of NDVI data (64 km^2) used in this continental-scale analysis precludes us from reporting the performance of PAs relative to area surrounding them.

Proposed mechanisms for the observed declines include summer drought stress, disturbance due to fire, insect and diseases, and nutrient limitations (Goetz et al., 2005). The IPCC AR4 reports significant warming over much of North America since the mid-1970s. While the warming may have promoted plant growth particularly in spring (Cayan et al., 2001; Zhou et al., 2001; Nemani et al., 2003b), it appears that accelerated warming since 2000 has increased summer moisture stress for natural vegetation. Recent changes in wildland fire regimes over much of the US have been linked to early onset of spring, coupled with increased summer moisture stress (Westerling et al., 2006). Each PA may have its own dominant mechanism responsible for the observed decline, and understanding the underlying mechanism for such a decline is a necessary first step for managing and forecasting ecosystem conditions. Satellite data, when properly calibrated and used, provide a valuable resource to identify and detect trends in ecosystem condition. Proper interpretation of such trends, however, requires integration of a variety of data sources and often supported by modeling. Though time-consuming and expensive, multi-scale analysis from satellite data is now possible as demonstrated in Neigh et al. (2008).

Detailed exploration of observed trends in peak photosynthetic capacity revealed no significant trend over Yosemite. However, much of the record between 1982 and 2006 is dominated by apparent drought-induced vegetation mortality and recovery patterns (Fig. 5a). For example, a multi-year drought in Yosemite from 1987–1990 (70% of normal precipitation) led to widespread tree mortality as reported by Guarin and Taylor (2005). As measured by peak NDVI, vegetation condition recovered from a low in 1988 to a peak in 1999, followed by a gradual decline towards another low resulting from a peak in drought-induced mortality in 2004. Though the 2002–2004 drought is not as severe (−13, −16, −30% of normal for 2002, 2003 and 2004 respectively) as that of 1987–1990, warmer temperatures may also have aggravated the climatic stress (Van Mantgem & Stephenson,

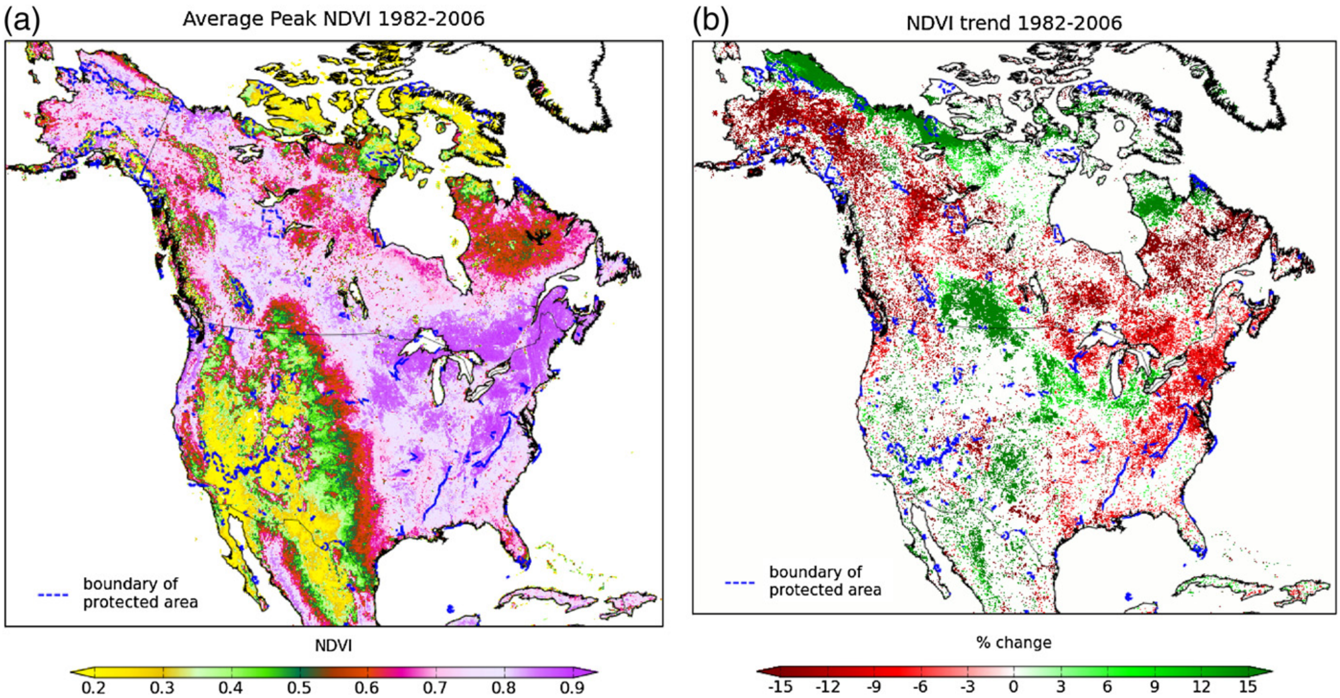

Fig. 4. (a) A twenty five year record (1982–2006) of average annual peak NDVI. (b) Declining trends in average peak NDVI, denoting stressed ecosystems, are being observed over many PAs of North America. PA boundaries, overlaid on the 8 km data NDVI data, are shown in blue. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2007). The Forest Service aerial mortality survey estimates that over 600,000 trees may have died during 2004 in and immediately adjacent to Yosemite compared to 79,000 during 2006, a year with normal climatic conditions.

During the overlap period (2001–2006) when data from both AVHRR and MODIS are available, NDVI anomalies over Yosemite from both sensors were similar, indicating a strong decline in 2004 (Fig. 5a). This correspondence is important because MODIS provides the high

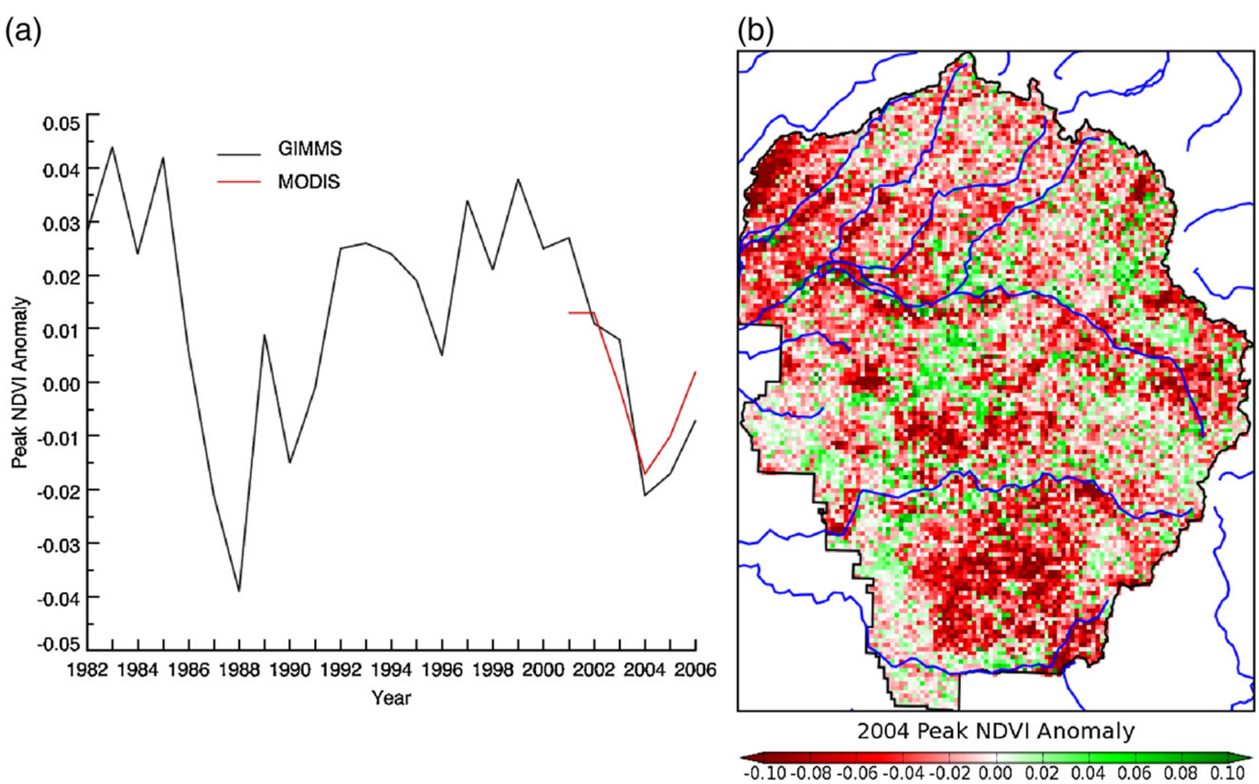

Fig. 5. (a) Although a time series of annual average peak AVHRR NDVI for the Yosemite National Park shows no significant trends from 1982–2006, drought between 1987 to 1990 and 2002 to 2004 are clearly defined, with subsequent evidence of recovery by 2006. Similarities in NDVI acquired by AVHRR since 1982 (black line) and MODIS since 2001 (red line) provide confidence in the continuity of the reflectance signal. (b) Change in MODIS NDVI at 500 m as a result of the 2004 drought compared to the 2001–2006 NDVI average, as estimated from MODIS NDVI 500 m data. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

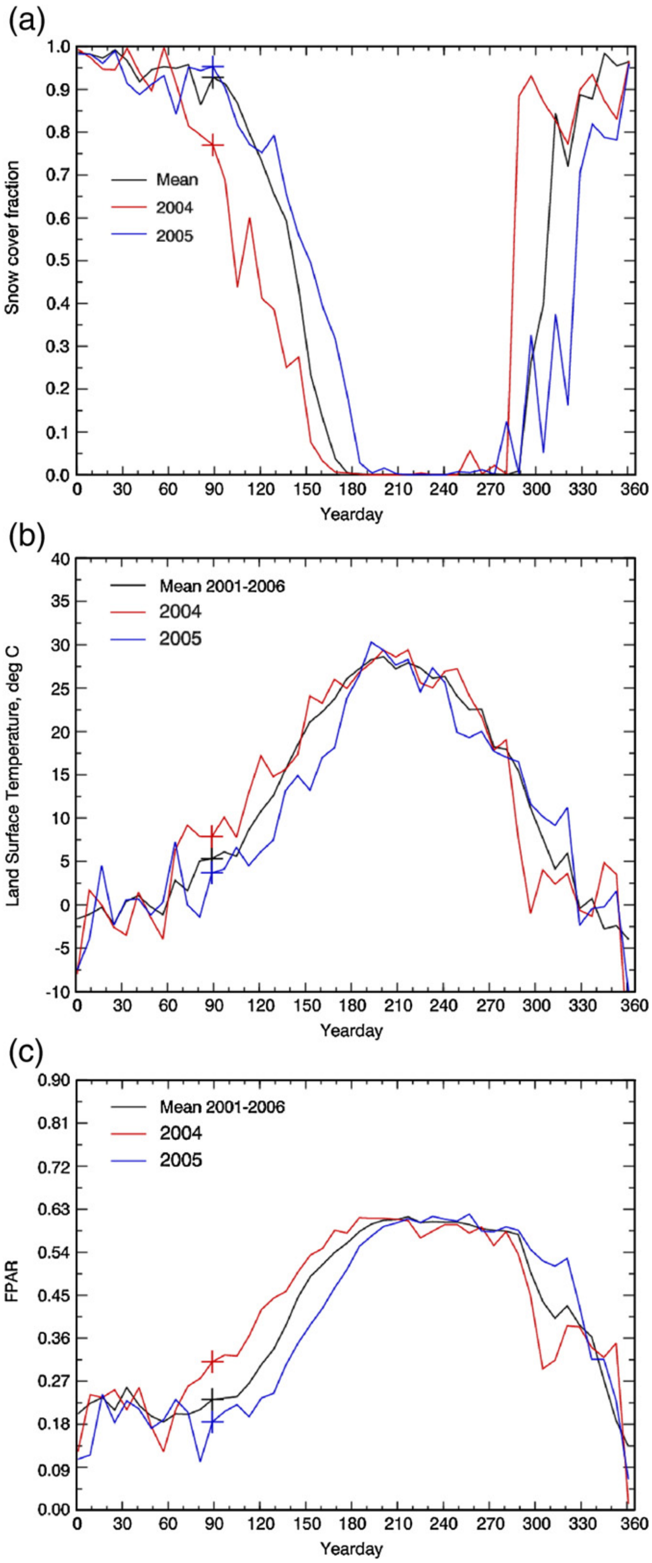

Fig. 6. A synergistic analysis of MODIS products: a) Snow cover, b) LST, and c) FPAR, provide a consistent portrait of the differences in growing season dynamics between 2004 and 2005. Park conditions on April 1st (+ symbol), considered an indicator of the upcoming growing season, provide a useful reference to compare different years.

spatial detail (500 m) while AVHRR data provide the long-term record. As the length of moderate resolution data-records increase this issue will be less important. The impact of the 2004 drought is spatially extensive as seen from MODIS 500 m data (Fig. 5b).

4.2. Monitoring interannual variability at Yosemite using TOPS

Capturing interannual variability is a pre-requisite for any monitoring system to be of use in detecting trends. Within the collection 4 MODIS record for Yosemite from 2001–2006, the years 2004 and 2005 represent two extremes providing an opportunity to test our methodology. Based on climatic data at Yosemite Headquarters, 2004 was a warm (2 °C above normal annual average temperature) and dry year (70% normal precipitation). March 2004 temperatures were 4 °C above normal, leading to early onset of snowmelt and runoff. 2005 was a cool (2 °C below normal) and wet (140% precipitation) year with cool spring temperatures. March temperatures were 2 °C below normal, delaying onset of snowmelt and runoff. The April 1st snowpack, measured at Tenaya lake (37.8380°N, 119.4480°W), was 24 cm in 2004 and 46 cm in 2005. Runoff measured at the Happy Isles USGS gauge on the Merced River was above normal for much of March 2004, indicating early snowmelt.

MODIS snow cover showed very different trajectories for the two years over Yosemite. Snow cover reached less than 5% of total park area in Yosemite nearly a month earlier in 2004 than in 2005 (Fig. 6a). Earlier snowmelt may have warmed surface temperatures, triggering park-wide higher springtime FPAR (Fig. 6b and c). The PAT phenology metric similarly indicates a much larger fraction of Yosemite to be

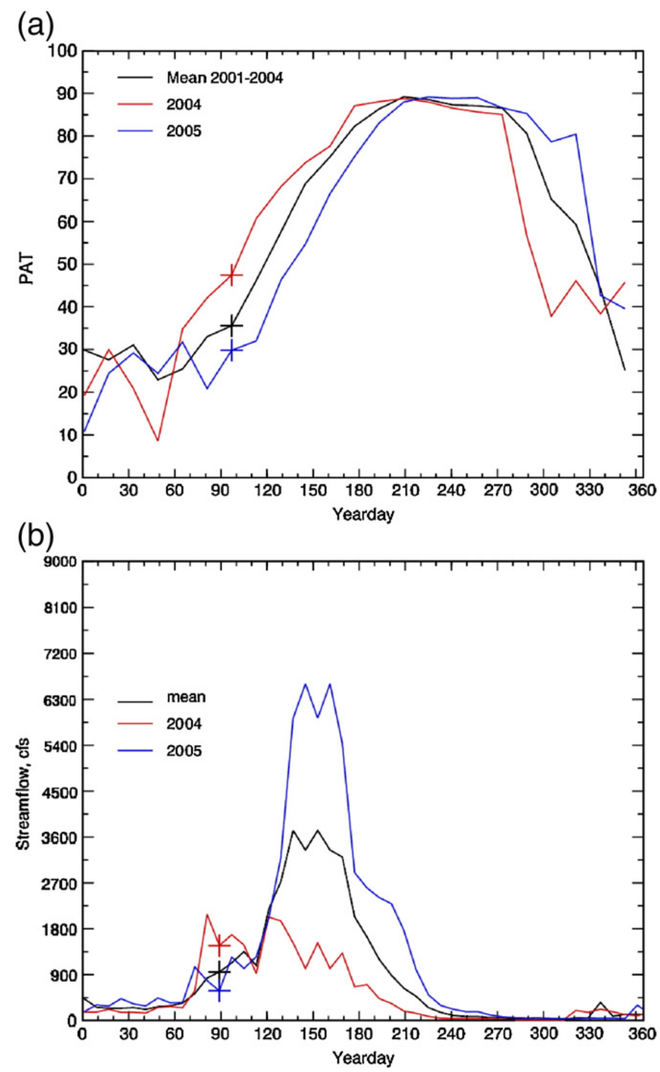

Fig. 7. Variations in the trajectories of (a) a park-wide PAT (Percent Above Threshold) phenology metric computed from satellite data for 2004 and 2005 are corroborated by (b) the changes in observed runoff patterns. + indicates the data point on April 1st.

above normal during much of spring 2004. Using April 1st values in each case as base values for assessing the two years (2004 and 2005), it is apparent that "normal" April 1st values are higher and reached earlier in 2004 than in 2005. The date at which the "normal April 1st" PAT and FPAR values are reached in 2004 is on the order of 45 days earlier than in 2005 (Fig. 7a). Daily flow measurements at the USGS Happy Isles gauge reflect a corresponding advancement in runoff from the Merced River watershed in 2004 as compared to 2005 (Fig. 7b).

By measuring the energy absorbed, reflected and emitted by the land surface, MODIS provides biophysical measures at the landscape-level that are integrative of ecosystem dynamics. Such measures are new to ecologists who are often comfortable with observing bud-break flowering and senescence of vegetation. We believe that integrating the two provides a more powerful metric than use of either approach individually. It is important to note that the observations compiled using TOPS included ground observations (runoff, snowpack), satellite observation (snow cover, LST, FPAR) and model-interpolated climate observations (temperature and precipitation), all of which paint a consistent picture of markedly different growing conditions during 2004 and 2005. This type of synergistic approach provides a much needed corroborative analysis that is often difficult to achieve from poorly instrumented ground-based networks alone. Another important feature of using MODIS data for monitoring is that every 8 days PA scientists and managers can monitor how a particular growing season is evolving, and evaluate that information in the context of historical averages.

4.3. Forecasting climate change impacts on Yosemite ecosystems

Modeled snow cover, runoff and GPP compared favorably with available observations (Fig. 8). TOPS snow cover simulations captured the seasonal dynamics of the MODIS-observed snow cover fraction ($R^2=0.92$, Fig. 8a); simulated and observed streamflows matched well in seasonal pattern and timing of peak and low flows ($R^2=0.68$, Fig. 8b). While TOPS-GPP compared well with observed GPP at the Blodgett Forest FLUXNET site, MODIS-derived GPP declined steeply during summer months (Fig. 8c). One possible explanation for this discrepancy is that the MODIS GPP product uses meteorological variables derived from a General Circulation Model with a large footprint. It is likely that meteorological conditions used for computing GPP were taken from a cell located either over the Central Valley or Western Nevada, which do not represent Yosemite well, as it is located in the middle of the two cells.

TOPS-derived interannual variability in peak monthly average GPP was able to capture observed variability in satellite-derived peak NDVI from 1982–2003 at Yosemite (Fig. 8d). As expected of a water-limited

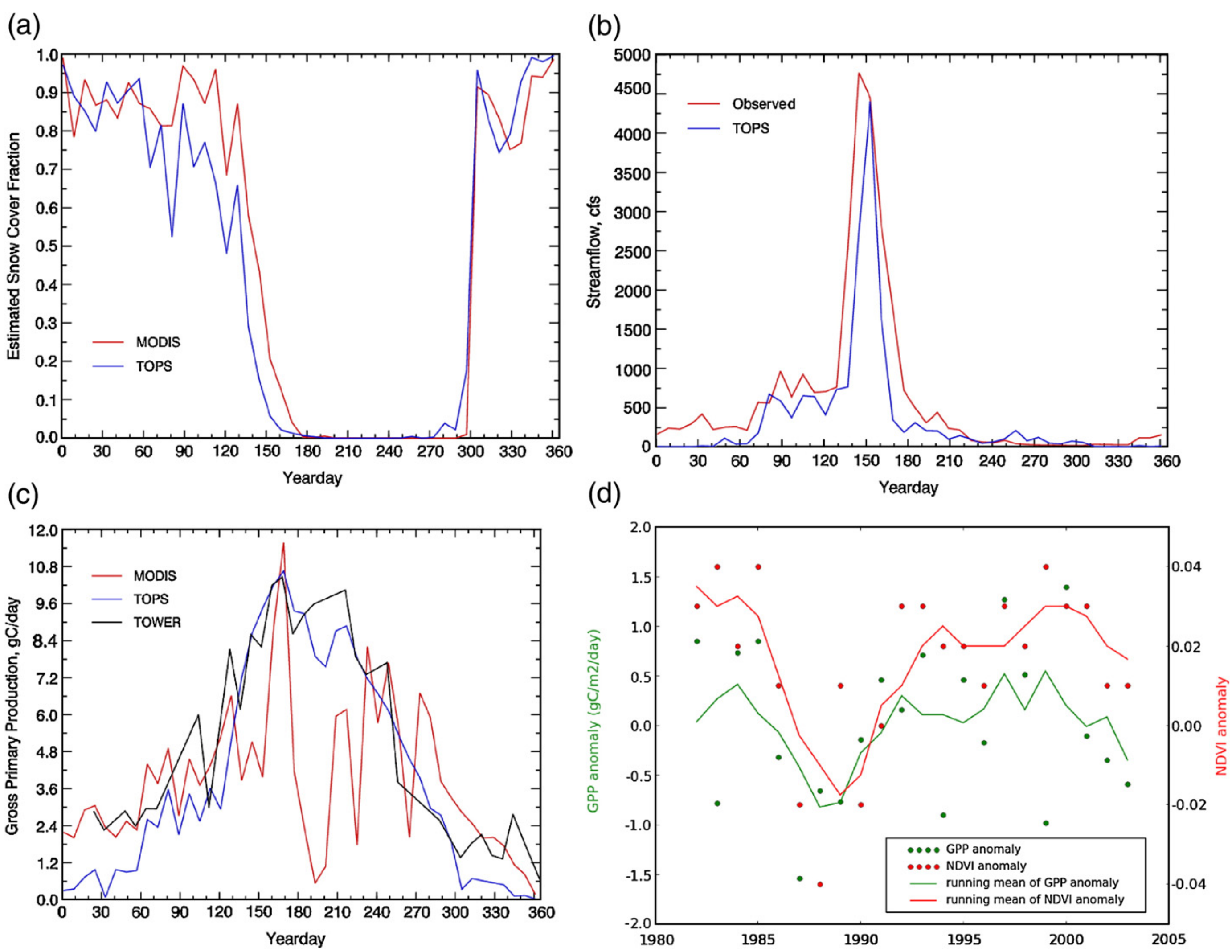

Fig. 8. TOPS simulations using observed climatic data over Yosemite capture seasonal changes in (a) snowcover, (b) streamflow, and (c) gross primary production, shown here for 2003. Tower-based GPP are from near-by Blodgett National Forest. (d) TOPS-derived peak monthly GPP also tracks interannual variability in NDVI observed from satellite data from 1982–2003, providing the necessary confidence to perform climate change impact simulations (actual simulations and observations are represented by points, while the lines correspond to moving averages).

system such as Yosemite, variations in annual precipitation explained nearly 55% of variation in modeled GPP. Interannual changes in temperature, negatively correlated with GPP, explained less than 20%.

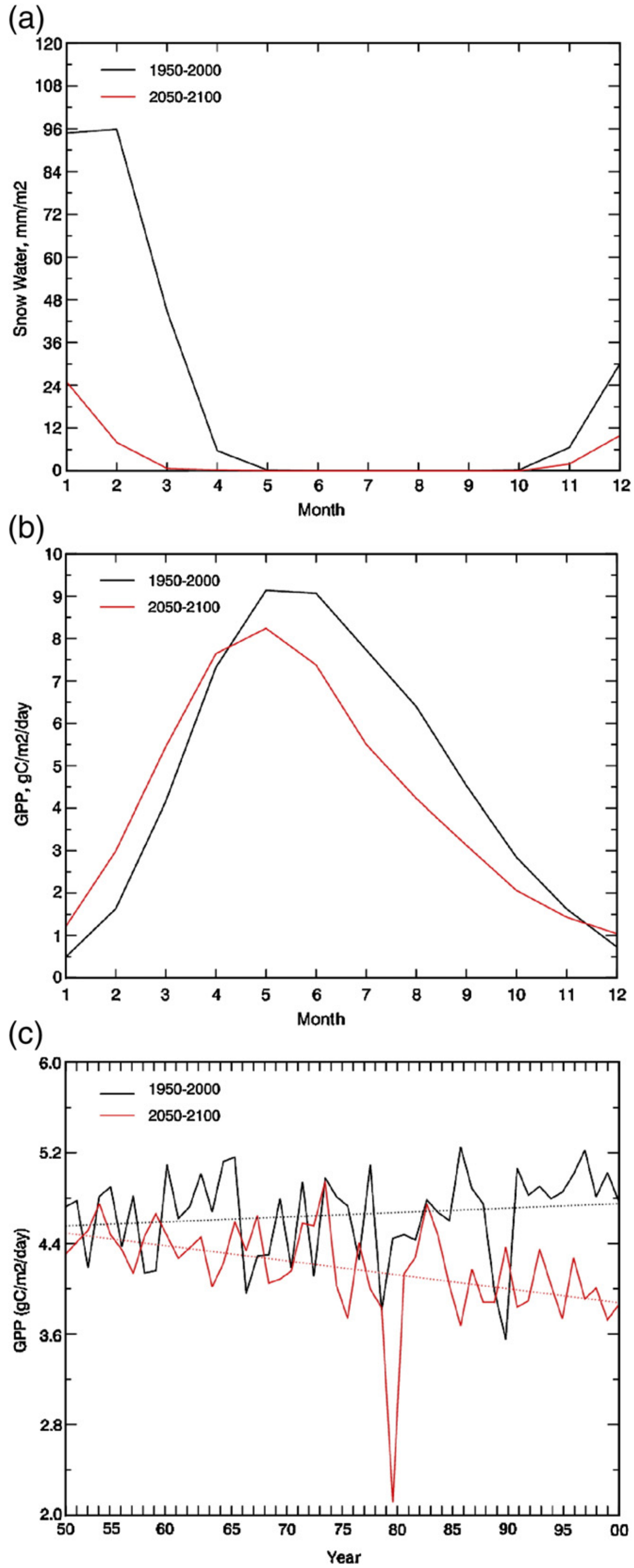

Fig. 9. Ecosystem model simulations show that warmer temperatures, an increase of 4–6 °C by year 2100, will have a significant impact on Yosemite ecosystem dynamics, including (a) decline in snowpack and earlier snowmelt, which, combined with increases in summer evaporative demand, lead to prolonged summer soil moisture stress and (b, c) reduced vegetation productivity in this water-limited ecosystem.

Consistent with earlier reports (Hayhoe et al., 2004), the largest changes in future climate for Yosemite are in temperature regimes, which are projected to warm 5 °C by the year 2100. Another robust feature of future climate scenarios for Yosemite is that of no detectable changes in precipitation. Such a scenario is quite similar to the climate regime from 1976–2006, when temperatures warmed dramatically without significant changes in total annual precipitation. When forced with past and future climates, TOPS produced long-term forecasts of dramatically different seasonal patterns in snow water content, GPP dynamics, and annual GPP. Peak snow water content is predicted to decline from an average of 95 mm in the current climate to an average of 25 mm in the future climate and much of the snow is predicted to melt by mid-March, nearly 45 days earlier under projected climate scenario (Fig. 9a). Warming also predicted to shift photosynthesis patterns in Yosemite towards early spring, with summer photosynthesis reduced by over 30% as a result of drought stress (Fig. 9b). Climate-induced stress from 1983–2004 has been identified as a possible cause of tree mortality in California's Sierra Nevada forests (Van Mantgem & Stephenson, 2007). Worsening climate-related stress levels predicted for 2050–2100 may result in a steady decline in annual GPP (Fig. 9c), which may bring about widespread changes in ecosystem dynamics and fire regimes.

4.4. Applicability of TOPS to PA management

We understand that PA scientists need information about climate change impacts on community composition, spread of invasive species, changes in population dynamics, and insect/disease outbreaks. Producing such domain-specific knowledge requires a multidisciplinary effort. Scientists working on PA ecosystems have a variety of modeling interests, and TOPS modeling capabilities are currently limited to ecosystem models that simulate only biogeochemical cycling. In order to facilitate the integration of new models, TOPS provides a system for describing new models in terms of their inputs and their outputs. These descriptions include specifications for the format, resolution, variables, and temporal and spatial extent of model parameters. These descriptions are then embedded in the domain descriptions of the model using the Data Processing Action Description Language (DPADL, Golden et al., 2003). While this method still lacks robustness and is not fully automated, it enables TOPS to integrate new models into the system faster than the manual integration that would otherwise be required.

Another feature of TOPS, beyond the scope of this paper, is a seasonal forecasting capability. TOPS, in much the same way that it estimates climate change impacts, provides seasonal forecasts of snow, soil moisture and productivity in response to projected climatic conditions up to seven months in advance. Several national and international agencies provide operational seasonal forecasts with varying degrees of skill (Robertson et al., 2004). PA managers may find a few of these predictions useful. For example, April snow pack at Yosemite is a good predictor of summer fire season (Guarin & Taylor, 2005) and has better than 50% predictability using December, January and February geopotential height at 500 mb and pacific sea surface temperature from the National Center for Environmental Prediction. On further evaluation and acceptance, such seasonal forecasts could provide regular estimates of short-term ecosystem-specific impacts.

5. Summary

We believe that TOPS, with its ability to integrate satellite, climate, and surface observations, provides a good first step towards building an integrated system to support tracking of many of the landscape-level vital signs indicators identified by the National Park Service I&M program. Operational, moderate resolution satellite data, microclimate mapping, and ecosystem simulation models, all integral parts of TOPS, can provide cost-effective yet valuable information for augmenting the often limited ground-based observing networks. Much work, however, is needed to cohesively present this information to practitioners who may have widely varying interests and backgrounds. We envision that the TOPS Data Gateway will serve this need, and will support automated analysis and organization of data into structured information, in addition to providing data access.

The utility of TOPS for tracking indicators of ecosystem condition in PAs has been demonstrated using examples at both the continental scale and the scale of an individual park. At the continental scale, analysis of vegetation condition in U.S. national parks using AVHRR and MODIS NDVI data reveals widespread declines in peak photosynthetic capacity in many parks from 1982 to 2006. At the scale of the individual park, TOPS currently supports landscape-level tracking of phenology, snow cover, productivity, climate, and vegetation condition for parks within the Sierra Nevada I&M network using data from satellites and ecosystem models. Analysis of multiple indicators clearly captures inter-annual phenological patterns, with the signal appearing in snow cover, NDVI, FPAR, and GPP, as well as ground-based observations of stream flow. Analysis of possible impacts of future climate scenarios on Yosemite National Park using TOPS indicates that increasing temperatures, reduced snow water, and an extended growing season are projected to decrease average photosynthesis by 30% during 2050–2099 relative to the period from 1950–1999, which was used as the baseline for the analysis.

Though TOPS currently emphasizes moderate resolution satellite data, incorporating higher-resolution data (e.g., Landsat images currently available from the Multi-Resolution Land Characteristics Consortium) is not difficult. Because TOPS follows the GEOSS architecture, which supports a much larger scope of applications, model interoperability is one aspect that is likely to continue to evolve and benefit systems such as TOPS in terms of both data and model integration.

One of the primary objectives of the NPS I&M program is to establish baseline conditions and document trends and patterns of change in key indicators. Our ultimate goal for TOPS is to be able to capture, serve, and analyze enough biophysical information about a PA that one could track the overall condition of the PA and communicate the condition of the PA to park management and the general public through concise metrics that are easily understood. For example, we envision that managers of a PA should be able to apply indicators from TOPS to contribute to a short annual summary that is supported by multiple levels of increasingly detailed information and data. While the full summary would include ground-based measures of other vital sign indicators, such as air quality, tree mortality, and species abundance, the TOPS contributions to such a summary may include measures of trends and anomalies in climate, snow cover, vegetation phenology, and productivity.

6. Acronyms

APAR	Absorbed Photosynthetically Active Radiation
AVHRR	Advanced Very High Resolution Radiometer
FLUXNET	Global network of micrometeorological towers
FPAR	Fraction of Photosynthetically Active Radiation Absorbed by plant canopies
GEOSS	Global Earth Observing System of Systems
GIMMS	Global Inventory Modeling and Mapping Studies
GPP	Gross Primary Production (gC m^{-2})
IPCC AR4	Intergovernmental Panel on Climate Change Fourth Assessment Report
I&M	Inventory and Monitoring
JDAF	Java Distributed Application Framework
LAI	Leaf Area Index (m^2/m^2)
LST	Land Surface Temperature (K)
MODIS	Moderate Resolution Imaging Spectroradiometer
NASA	National Aeronautics and Space Administration
NDVI	Normalized Difference Vegetation Index (dimensionless)
NOAA	National Oceanic and Atmospheric Administration
NPP	Net Primary Production (gC m^{-2})
NPS	National Park Service
OGC	Open Geospatial Consortium
PA	Protected Areas
SOGS	Surface Observations Gridding System
TOPS	Terrestrial Observation and Prediction System
WCS	Web Coverage Service
WMS	Web Mapping Service

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